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Analyses of the Associated Technical and Economic Risks of the Simple and Intercooled Brayton Helium Recuperated Gas Turbine Cycles for Generation IV Nuclear Power Plants

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Abstract

The Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) are highly efficient Brayton helium gas turbine cycles, designed for the Gas-cooled Fast Reactor (GFR) and Very-High-Temperature Reactor (VHTR) Generation IV (Gen IV) Nuclear Power Plants (NPPs). This paper documents risk analyses which considers technical and economic aspects of the NPP. The sensitivity analyses are presented that interrogate the plant design, performance and operational schedule and range from component efficiencies, system pressure losses, operating at varied power output due to short term load-following or long term reduced power operations to prioritise other sources such as renewables. The sensitivities of the economic and construction schedule are also considered in terms of the discount rates, capital and operational costs and increased costs in Decontamination and Decommissioning (D&D) activity due to changes in the discount rates. This was made possible by using a tool designed for this study to demonstrate the effect on the 'non-contingency' baseline Levelised Unit Electricity Cost (LUEC) of both cycles. The SCR with a cycle efficiency of 50%, has a cheaper baseline LUEC of $58.41/MWh in comparison to the ICR (53% cycle efficiency), which has a LUEC of $58.70/MWh. However, the cost of the technical and economic risks is cheaper for the ICR resulting in a final LUEC of $70.45/MWh (ICR) in comparison to the SCR ($71.62/MWh) for the year 2020 prices.

Keywords: Gen IV, Efficiency, Work, Cycle, Nuclear Power Plants, Performance, Simple, Intercooled, Levelised Unit Electric Cost.

NOMENCLATURE

Notations

A	Area (m^2)
C	Cash Flow
Cp	Spec. Heat of Gas at Constant Pressure (J/kg K)
CW	Compressor Work (W)
F	Fuel Cycle Component
J	Number of Periods
m	Mass Flow Rate (kg/s)
$NDMF$	Non-Dimensional Mass Flow
P	Pressure (Pa) or Power (Economic Analysis)
PW	Power
PR	Pressure Ratio
Q	Reactor Thermal Heat Input
q	Heat Flux (W/m^2)
r	Discount Rate
SW	Specific Work/Power Output (J/kg K)
T	Temperature(K or °C)/Time/Date (Economic Analysis)
TR	Temperature Ratio (T_4 / T_1; expressed in Kelvin)
TW	Turbine Work (W)
t	Time or Date
W	Work (W)
UW	Useful Work (W)
X	Real Discount Rate

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Greek Symbols

γ Ratio of Specific Heats

Δ Delta, Difference

ε Effectiveness (Cooling)

η Efficiency

θ Referred Temperature Parameter

δ Referred Pressure Parameter

Subscripts

$blade$ Turbine Temperature (also known as Blade Temp.)

c Compressor

c_{in} Compressor Inlet

c_{map} Compressor Map

c_{out} Compressor Outlet

$cool$ Cooling

$coolant$ Compressor Exit Coolant

$e/elec$ Power for Electrical Conversion

$elec\_annual$ Annual Electricity

gas COT/TET

he Helium

he_{min} Helium with minimum gas conditions

ic Intercooled Cycle; intercooled coefficient

is_c Isentropic (Compressor)

is_t Isentropic (Turbine)

j Period number

map_{He} Map adapted for helium gas

map_{Air} Map adapted for air

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MHR Reactor (Heat Source)

MHR_{in} Reactor (Heat Source) Inlet

MHR_{loss} Reactor (Heat Source) Pressure Losses

MHR_{out} Reactor (Heat Source) Outlet

$NDMF_{Plant}$ Plant Non-Dimensional Flow Conditions

op Operation

pc_{in} Precooler Inlet (also applicable to intercooler)

pc_{loss} Precooler Pressure Losses (same as above)

pc_{out} Precooler Outlet (same as above)

re Recuperator

re_{cold} Recuperator cold side

re_{hot} Recuperator hot side

re_{HPloss} Recuperator High Pressure Losses

re_{LPloss} Recuperator Low Pressure Losses

re_{real} Recuperator Real (specific heat transfer)

re_{max} Recuperator Max (specific heat transfer)

th Thermal Power

t Turbine

t_{map} Turbine Map

t_{out} Turbine Outlet

t_{in} Turbine Inlet

Superscripts

' Recuperator inlet conditions

L/L_{econ} Plant Operational Life

Abbreviations

BCC Baseline Capital Costs

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C	Compressor
CDD	Decomm. Cost
CFC	Capitalised Financial Cost
CH	Precooler
CIT	Core Inlet Temperature
COT	Core Outlet Temperature
DD/D&D	Decontamination and Decommissioning / Constant Dollar D&D Payment
DP	Design Point
EMWG	Economic Modelling Working
FCR	Fixed Charge Rate
GEN IV	Generation IV
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
HP	High Pressure
HPC	High Pressure Compressor
HE	Recuperator
IC	Intercooler
ICR	Intercooled Cycle Recuperated
IDC	Interest During Construction
IPC	Inventory Pressure Control
ISA	International Standard Atmosphere
LCC	Levelised Capital Cost
LFCC	Levelised Fuel Cycle Cost
LP	Low Pressure
LPC	Low Pressure Compressor
LUEC	Levelised Unit Electricity Cost
LWR	Light Water Reactor
MOX	Mixed Oxide

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NPP	Nuclear Power Plant
NTU	Number of Transfer Units
NuTERA	Nuclear Techno-Economic and Risk Assessment
OD	Off-Design
ODP	Off-Design Point
O&M/OM	Operation and Maintenance
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
SCR	Simple Cycle Recuperated
SFF	Sink Fund Factor
SOC	Specific Overnight Costs
TCC	Total Capital Costs
TCIC	Total Capital Investment Costs
TET	Turbine Entry Temperature
TOCC	Total Overnight Construction Cost
VHTR	Very High Temperature Reactor

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1. Introduction

Generation IV (Gen IV) reactor performance and economics are key imperatives for the design and competitiveness of Nuclear Power Plants (NPP) in comparison to the incumbent design and other sources of power generation. An understanding of the technical aspects of any NPP requires in-depth knowledge of the design requirements which need to be underpinned by sound economics to demonstrate viability of the NPP project. With the availability of several cycle choices, it is important to perform comparative techno-economic analyses to improve the understanding of the technology and aid the decision-making process. Such analyses needs to be complemented with an understanding of the risks in order to quantify their effects on the Levelised Unit Electricity Cost (LUEC) of the plant for the purpose of providing contingencies for the plant capital investment, operations and end of life. Thus, the objective of this paper is to conduct technical and economic risk analyses associated with plant design, performance operation and capital finance and to assess the effect on the 'non-contingency' baseline LUEC. The analyses is performed using a tool specifically design for this study to analyse the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) in a closed Brayton direct configuration using helium as the working fluid.

2. Generation IV (Gen IV) Systems

The Gas-Cooled Fast Reactor System (GFR) and Very-High-Temperature Reactor System (VHTR) are the focus of this paper. The GFR makes use of helium as the coolant with a high temperature combined with a fast spectrum nuclear core. The Core Outlet Temperature (COT) is between 850-950°C and is configured using an efficient direct thermodynamic Brayton gas turbine cycle. Single phase cooling is provided by the helium coolant due to its chemical inertness, stability and neutronic transparency. The VHTR as a thermal reactor also has high temperature capability, which is also cooled using helium in its gaseous phase. The core can be a prismatic block or a pebble bed. Moderation is provided by graphite in the solid state. The core delivers a COT of 750-1000°C meaning significant increases in cycle efficiency are expected without altering the gas properties of helium. Graphite also possesses the necessary mechanical properties for moderation. The list of on-going and planned demonstration projects are described and discussed in [1].

3. The Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) Helium Brayton Cycles

The SCR includes the compressor and turbine components which form the plant turbomachinery. The Compressor Work (CW) is less than the work requirement generated by the Turbine Work (TW). This means that the Useful Work (UW), which is the remaining work after the compressor load requirements have been met, is used to drive the generator load. Limitations to

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this process are brought on by component inefficiencies during the compression and expansion phases. The component inefficiencies means that the compression and expansion phases are not isentropic [2]. Consequentially, the heating and cooling stages of the cycle when heat exchangers are not taken into account, are not isobaric. This effect means that the cycle experiences losses that translate into additional work input which is required for the helium to be compressed to some pressure due to the increase in temperature. This high temperature translates into higher than preferred exit temperature at the compressor. Due to the fact that the heat added into the cycle is not isobaric, the total gas exit pressure is reduced accordingly [2]. This means that the total power extracted from the cycle is less than ideal due to the reduced gas exit pressure combined with reduced component efficiencies. The turbine exhaust heat is hotter than expected, which in turn influences the inlet compression temperature as it becomes hotter than necessary.

A typical NPP would include a precooler and a recuperator in addition to the turbomachinery. The addition of a precooler reduces the turbine exhaust gas temperature using a cooling medium such as seawater. The cooled helium at the compressor entry is necessary at the cycle inlet because it reduces the CW but in turn, the compressor exit temperature rises but not enough for the cycle. This leads to increases in the reactor input thermal power beyond the reactor design intent. Due to the thermal power being fixed for a given COT, the precooler alone will not provide the necessary Specific Work (SW) and cycle efficiency and reduces the plant economics. The recuperator is introduced to improve the economics of the cycle. This is achieved by exchanging the heat from the turbine exhaust gas to the helium upstream at the inlet of the reactor. This raises the temperature of the helium thereby reducing the amount of thermal heat input and reactor power to have a positive effect on cycle efficiency.

The SCR and ICR comprise all of the components as stated above. However, the ICR has an intercooler and an additional compressor which are both downstream of the first compressor. The ICR improves the SW and UW by reducing the compressor work in comparison to the SCR. The helium downstream of the first compressor is reduced to a lower temperature as it passes through the intercooler, before entering the second compressor upstream, with some negligible reductions in pressure observed.

The thermodynamics which results from changing to helium in a nuclear gas turbine have been extensively covered in [3]. The study is also documented in [7] and [8] and focuses on off-design, control and transient operational modes of a helium gas turbine, which is also applicable to the plant operations for this study. With present day technologies, the potential for reliable helium gas turbines has never been greater. Improvements such as magnetic bearings and high performance

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adjustable seals to reduce leakage and helium ingress in the bearing assemblies, supported by precision manufacturing and computational power help make this a possibility.

4. Method of Modelling of Nuclear Power Plants - Technical Performance Model

When focusing on the technical model, this part of the tool was created using FORTRAN. The tool can determine the mass flow rate, and pressures and temperatures for each component based on known cycle inlet conditions and COTs, with consideration of component efficiencies, pressure losses and cooling requirements. This enables the NPP output and cycle efficiency to be derived. The tool is also capable of analysing the effects on cycle output, capacity and efficiency by investigating changes to any of the above parameters. In addition, the tool includes component maps and algorithms to calculate the optimal Off-Design Points (ODPs) for long term operation at reduced power settings or where changes in ambient temperature from Design Point (DP) is observed. Whereby changes in ambient temperature are varied and demand load-following or reduced power is required for short term operation, the NPP can be regulated using Inventory Pressure Control (IPC). The tool is capable of modelling the typical load-following characteristics. Figures 1 and 2 illustrate typical schematics of the SCR and the ICR, with Table 1 providing the key technical DP values which underpins the plant configurations for the economic analyses.

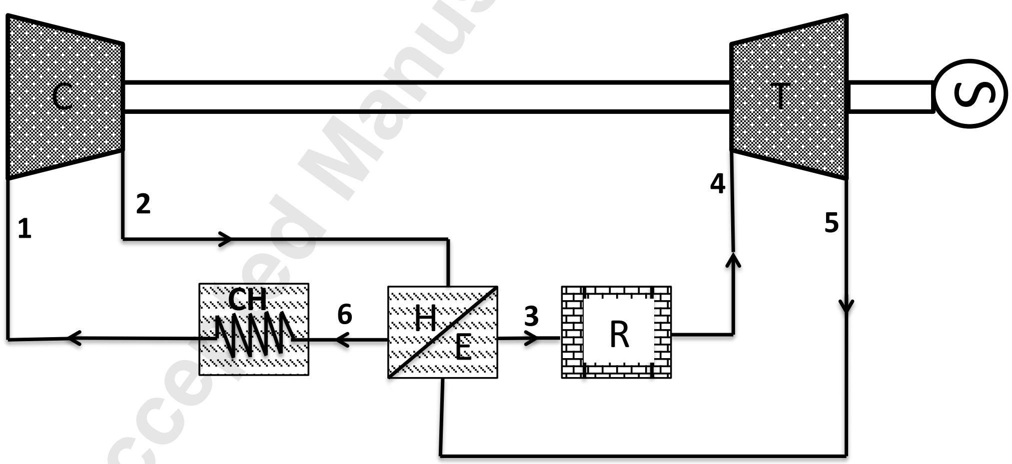

Figure 1 – The Simple Cycle Recuperated (SCR)

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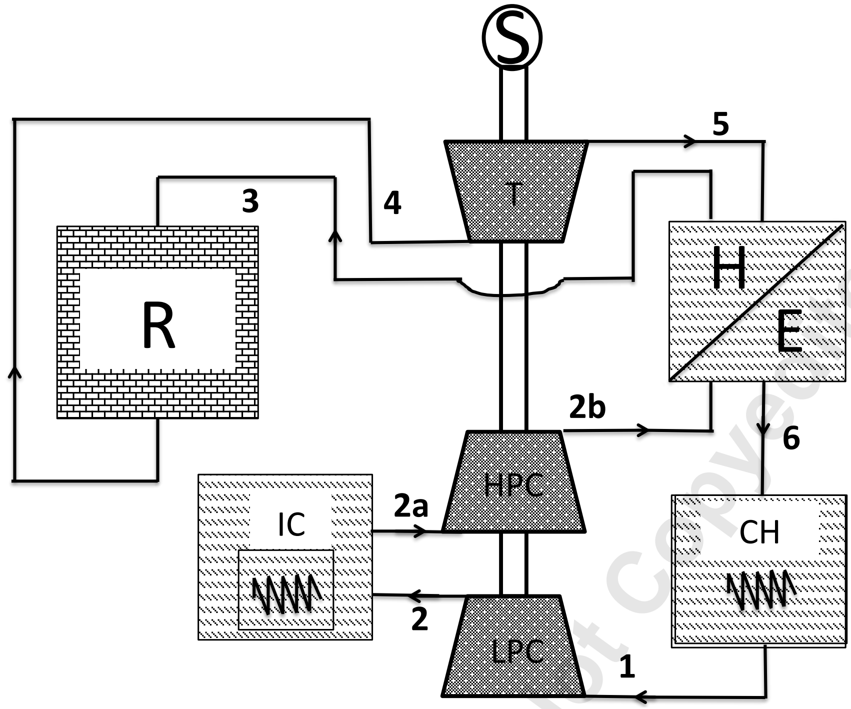

Figure 2 – The Intercooled Cycle Recuperated (ICR)

Table 1 – SCR and ICR Technical Design Point Input Values

Design Point Performance Input Parameters	SCR	ICR	Units
Inlet Temp. (T_1)	28	28	°C
TET (Core Outlet Temp) (T_4)	950	950	°C
Inlet Pressure (P_1)	3.21	3.21	MPa
Mass flow rate at inlet (m_1)	410.4	410.4	kg/s
Compressor Efficiency (Isentropic)	90	90	%

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Turbine Efficiency (Isentropic)	**94.5**	**94.5**	**%**
Recuperator Effectiveness	**96**	**96**	**%**
Pressure Loss (Precooler)	**2.5**	**2.5**	**%**
Pressure Loss (Intercooler, ICR only)	**-**	**2.5**	**%**
Pressure Loss (Reactor)	**2**	**2**	**%**
Pressure Loss (Recup. HP side)	**6 combined**	**6 combined**	**%**
Pressure Loss (Recup. LP side)			
Reactor Cooling flow (% of Mass flow rate)	**0.25**	**0.25**	**%**

The equations implemented within the code environment of the technical model are described in the proceeding sections for steady state design point calculations against each component and cycle. The model was used to match known NPPs configurations in the public domain with the results proving to be satisfactory.

4.1 <u>Compressor</u>

Prerequisite parameters for performance design considerations of both compressors include the compressor pressure ratio (PR), compressor inlet conditions (temperature, pressure and mass flow), component efficiency and the working fluid gas properties (Cp and γ). The compressor outlet pressure (Pa) is:

$$P_{c_{out}} = P_{c_{in}} \cdot PR_c \qquad (1)$$

The isentropic efficiency of the compressor is $\frac{T_{rise_{ideal}}}{T_{rise_{actual}}}$ and is also indicative of the specific work input or total temperature increase. Thus, the temperature (°C) at the exit can be derived from the inlet temperature, PR, isentropic efficiency and ratio of specific heats:

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$$T_{c_{out}} = T_{c_{in}} \cdot \left[1 + \frac{\left(\frac{P_{c_{out}}}{P_{c_{in}}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{is_c}} \right] \tag{2}$$

The mass flow (kg/s) at inlet is equal to the mass flow at outlet as there are no compositional changes:

$$m_{c_{out}} = m_{c_{in}} \tag{3}$$

The CW (W) is the product of the mass flow, specific heat at constant pressure and the temperature delta:

$$CW = m_c \cdot Cp_{he} \cdot (\Delta T_c) \tag{4}$$

$$\text{whereby } \Delta T_c = T_{c_{out}} - T_{c_{in}} \tag{5}$$

Bypass splitters are incorporated within the performance simulation tool, to allow for compressed coolant to be bled from the compressor(s) for Reactor Pressure Vessel (RPV) cooling and turbine cooling. The method of estimating the required turbine cooling is detailed in [6].

4.2 Turbine

Prerequisite parameters of the turbine include the turbine inlet conditions (temperature, pressure and mass flow), the pressure at outlet, component efficiency and the working fluid gas properties (Cp and γ).

The temperature (°C) at the outlet is derived from the following expression:

$$T_{t_{out}} = T_{t_{in}} \cdot \left\{ 1 - \eta_{is_t} \left[1 - \left(\frac{P_{t_{out}}}{P_{t_{in}}}\right)^{\frac{\gamma-1}{\gamma}} \right] \right\} \tag{6}$$

As with the compressor, eqs (3) and (4) also apply to the turbine for mass flow (kg/s) conditions and TW (W) but:

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$$\Delta T_t = T_{t_{in}} - T_{t_{out}} \quad (7)$$

A mixer is incorporated within the performance simulation tool to allow for the coolant to mix with the hot gas to simulate turbine cooling.

4.3 Precooler and Intercooler (ICR Only)

Prerequisite parameters for the precooler and intercooler takes into account that the precooler is upstream of the compressors and the intercooler (ICR only) is downstream of the first compressor and upstream of the second compressor. As a result, the compressor inlet temperature and pressure are of importance including the pressure losses. The conditions for the precooler are as follows:

$$T_{pc_{out}} = T_{c_{in}} \quad (8)$$

$$P_{pc_{in}} = P_{pc_{out}} \cdot \left(1 + \Delta P_{pc_{loss}}\right) \quad (9)$$

$$m_{pc_{out}} = m_{pc_{in}} \quad (10)$$

With regard to the intercooler, eqs (8), (9) and (10) apply but are differentiated within the code to ensure exclusivity to the respective components. The for ICR, the addition of a second compressor for the intercooled cycle means that the PR for both compressors is determined as:

$$PR_{ic} = \sqrt[ic]{PR} \quad (11)$$

4.4 Modular Helium Reactor

As a heat source with inevitable pressure losses, the prerequisite are the thermal heat input from burning the fuel and the known reactor design pressure losses.

The heat source does not introduce any compositional changes thus mass flow (kg/s) is:

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$$m_{MHR_{out}} = m_{MHR_{in}} \tag{12}$$

Pressure (Pa) taking into account losses (%):

$$P_{MHR_{out}} = P_{MHR_{in}} \cdot \left(1 - \Delta P_{MHR_{loss}}\right) \tag{13}$$

and the thermal heat input (Wt) is:

$$Q_{MHR} = m_{MHR_{in}} \cdot Cp_{he} \cdot \ (\Delta T_{MHR}) \tag{14}$$

whereby

$$\Delta T_{MHR} = \ T_{MHR_{out}} - \ T_{MHR_{in}} \tag{15}$$

A mixer is incorporated within the code to allow for the coolant to be mixed with the heated fluid upstream of the reactor, in order to simulate reactor vessel cooling.

4.5 Recuperator

The calculation method for the rate of heat transfer is based on the Number of Transfer Units (NTU) method, which has been documented by [7] and applied for complex cross flow heat exchangers by [8]. The algorithm in the code ensures satisfactory results and numerical stability.

Prerequisite parameters include the recuperator effectiveness, hot and cold inlet conditions (pressure and temperature) and the delta pressures due to losses at high and low pressure sides.

The effectiveness of the recuperator is given as:

$$\varepsilon_{re} = \frac{q_{re_{real}}}{q_{re_{max}}} \tag{16}$$

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The maximum amount of heat flux (W/m²) of the recuperator $q_{re_{max}}$ must consider the hot and the cold inlet conditions. It must also consider the minimum specific heat because it is the aspect of the fluid with the lowest heat capacity to experience the maximum change in temperature. This is expressed as:

$$q_{re_{max}} = \frac{Cp_{he_{min}} \cdot \left(T'_{re_{hot}} - T'_{re_{cold}}\right)}{A} \tag{17}$$

and the real heat flux (W/m²) is:

$$q_{re_{real}} = \frac{Cp_{he_{hot}} \cdot \left(T'_{re_{hot}} - T_{re_{hot}}\right)}{A} = \frac{Cp_{he_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)}{A} \tag{18}$$

With helium as the working fluid, Cp is considered to be constant, thus $Cp_{he_{min}} = Cp_{he_{cold}} = Cp_{he_{hot}}$ in the energy balance equation. The temperatures at the hot and cold ends can be obtained when considering eq (18) (either hot or cold sides) and considering an arbitrary effectiveness. The temperature for the cold end (°C) is then expressed as:

$$T_{re_{cold}} = T'_{re_{cold}} + \left[\varepsilon_{re} \cdot \left(T'_{re_{hot}} - T'_{re_{cold}}\right)\right] \tag{19}$$

With $Cp_{he_{min}} = Cp_{he_{cold}} = Cp_{he_{hot}}$, the energy balance is:

$$\left[m_{re_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)\right] = \left[m_{re_{hot}} \cdot \left(T'_{re_{hot}} - T_{re_{hot}}\right)\right] \tag{20}$$

thus, the hot outlet (°C) is:

$$T_{re_{hot}} = T'_{re_{hot}} - \left[\frac{m_{re_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)}{m_{re_{hot}}}\right] \tag{21}$$

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With regard to pressures, the exit conditions can be calculated if the pressure drops (%) across the hot and cold sides are known:

$$P_{re_{cold}} = P'_{re_{cold}} \cdot \left(1 - \Delta P_{re_{HPloss}}\right) \tag{22}$$

$$P_{re_{hot}} = P'_{re_{hot}} \cdot \left(1 - \Delta P_{re_{LPloss}}\right) \tag{23}$$

Due to no compositional changes, mass flow rate (kg/s) conditions are:

$$m_{re_{hot}} = m'_{re_{hot}} \tag{24}$$

$$m_{re_{cold}} = m'_{re_{cold}} \tag{25}$$

4.6 *Cooling Calculations*

The prerequisites for calculating the cooling flow, which is required to operate the turbine at the extreme temperatures are the turbine metal temperature (simply known as blade metal temperature), compressor exit coolant temperature, COT/TET (simply known as gas) and cooling effectiveness. The cooling flow is a percentage of the mass flow and is taken from the compressor exit. The cooling effectiveness (<1) is expressed as:

$$\varepsilon_{cool} = \frac{(T_{gas} - T_{blade})}{(T_{gas} - T_{coolant})} \tag{26}$$

4.7 *Cycle Calculations*

The UW, SW and thermal efficiency output values are of interests after executing each set of station parametric calculations. The UW (We) that is the work available for driving the load is:

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$$UW = TW - CW \tag{27}$$

whereby CW is the is the compressor(s') work requirement to be delivered by the turbine. The specific work (SW) or capacity of the plant (J/kg K) is:

$$SW = UW/m \tag{28}$$

and the thermal efficiency (%) of the cycle is:

$$\eta_{th} = UW/Q_{MHR} \tag{29}$$

4.8 Long Term Off-Design Point Calculations

Long term operation indicates the need to operate at optimum reduced power settings due to prioritisation of other generating sources such as renewables over the NPP. When calculating the ODP performance for long term operation the maps become part of the process. Furthermore, they are scaled for capacity purposes to suit the particular plant cycle configuration, thereby avoiding the use of multiple maps. For constant speed steady state ODP performance, the temperature inlet conditions into the compressor is expressed as a referred parameter for standard ISA conditions of temperature for the purpose of determining the reference speed curve. This is corrected into a dimensionless parameter for the purpose of adapting the map for helium and is expressed as:

$$CN = \frac{N}{\theta}_{Map_{Air}} = \frac{N}{\sqrt{(\gamma \cdot R \cdot T_{c_{in}})}}_{Map_{He}} \tag{30}$$

Equation 30 defines the speed as the handle and determines the corresponding polynomial speed curve for the inlet temperature. Once the inlet conditions are defined, the model proceeds to calculate each component station condition.

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Ignoring component geometry, the NDMF considers the mass flow rate, temperature and pressure at inlet and the gas properties:

$$NDMF = \frac{m \cdot \sqrt{(\theta)}}{\delta}_{Air} = \frac{m \cdot \sqrt{(T_{S_{in}} \cdot R)}}{P_{S_{in}} \cdot \sqrt{(\gamma)}}_{He} \qquad (31)$$

With consideration of a given matching tolerance, the NDMF compatibility is expressed as:

$$NDMF_{C_{map}} \cdot \frac{P_1}{P_2} \cdot \frac{P_2}{P_3} \cdot \frac{P_3}{P_4} \cdot \sqrt{\frac{T_4}{T_1}}_{NDMF_{Plant}} = NDMF_{t_{map}} \quad (32)$$

whereby Eq. (32) is for the SCR (see Figure 1) and also applicable to the ICR. For the ICR, the sequence in Eq. (32) begins from station 2a (see Figure 2). The complete process of matching and calculating the ODP performance for long term operation is detailed in [9].

4.9 Short Term Off-Design Point Calculations

With regard to load-following operations for short term Off-Design (OD) operation, the capabilities for steady state and transient inventory pressure control relies on the model to debit and credit the flow at the subject stations. For transient conditions, the calculations are repeated to represent incremental changes of the mass flow rate (kg/s) to simulate the control method. The process including the control strategies applicable are described in [10], with load following demonstrated in [11].

5. Method of Modelling of Nuclear Power Plants - Economic Model

A top down approach was adopted to estimate the component costs. The component costs are primarily based on [12] which provides the costing for the helium GT-MHR plant. Other cost methods were derived to estimate the turbomachinery and the heat exchangers using non-dimensional functions that account for mass flows, temperatures and pressures. Scaling factors were also appropriately applied where necessary using the power output. However, the derived costs using the non-

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dimensional functions are comparable to those in [12] when reverse inflation is applied. The main equations that define the Total Capital Investment Costs (TCIC), the Specific Overnight Costs (SOC) and the levelised costs for the economic model are described in the proceeding sections. The calculation of the TCIC takes into consideration typical cash flow, the Total Capital Costs (TCC) and the Interest During Construction (IDC) in accordance with [13], [14]. The economic model was used to match the economic assessments of the GTHTR300 NPP detailed in [15], [16] with satisfactory results.

5.1 Interest During Construction (IDC)

The IDC (constant dollars) which is applied to the capital loan for the period the plant is being built is determined as follows:

$$IDC\colon \sum_{j=1}^{j=J} C_j \cdot \left[(1+r)^{t_{op}-j} - 1\right] \tag{33}$$

whereby j is the period number, J is the number of periods (quarters or years of construction), C_j is cash flow for year or quarter and reflects the 'beginning of the borrowing' period, r is the real discount rate expressed annually or quarterly as appropriate and t_{op} is the quarterly or yearly commercial operation.

5.2 Total Capital Investment Cost (TCIC)

The TCIC ($) is determined as:

$$TCIC = BCC + TOCC + CFC \tag{34}$$

whereby BCC is the Baseline Construction Cost derived from estimating the direct and indirect costs using either a top down or bottom up approach, TOCC is the Total Overnight Construction Cost, which includes the cost of the fuel, contingencies e.t.c. and CFC is the Capitalised Financial Cost.

5.3 Specific Overnight Cost (SOC)

The SOC ($/kWe) is the cost derived after the TCIC cost is calculated. This is expressed as:

$$SOC = \frac{\frac{TCIC}{1000}}{PW_{elec}} \tag{35}$$

whereby the PW_{elec} is the power output at the generator (We).

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5.4 Levelised Capital Cost (LCC)

As part of the assumptions of equal energy generation as advised by the GIF Economic Modelling Working Group (EMWG) [13], the LCC ($/kWh) is:

$$LCC = \frac{FCR \cdot TCIC}{P_{elec\_annual}} \tag{36}$$

whereby the FCR is the Fixed Charge Rate and P_{elec_annual} is the annual electricity production for a single plant (kWh/year). The FCR is typically used to account for various entities such as the interim replacements, return on capital, income and property tax and depreciation. For Gen IV NPP projects, the cost estimation tax and depreciation are ignored. This is due to the process being generalised and is not inclusive of tax [13]. For this reason, it is calculated as a capital recovery factor or the principal loan repayment over a time period:

$$FCR = \frac{X}{\left[1-(1+X)^{-L_{econ}}\right]} \tag{37}$$

whereby X represents the real discount rate of 5% or 10%, and L_{econ} represents the operational life of the plant. The TCIC plus the cost of the construction loan is converted into a mortgage-type loan, which recuperates the capital investment (principal loan including the interest) over the life of the plant [13].

5.5 Levelised Operation and Maintenance (O&M) Cost

The levelised O&M cost ($/kWh) is the overall total annual costs divided by the annual electricity produced. The main assumption here is that the constant dollar costing will be the same for the entire plant life.

5.6 Levelised Fuel Cycle Cost

The Levelised Fuel Cycle Cost (LFCC) is expressed as:

$$LFCC = \sum i \sum_{t=t_0-T_1}^{t=t_0+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_0)}} \tag{38}$$

whereby t_0 is the reference commissioning date, L is the operational life of the plant, T_2 is the maximum value of lag time (in the back-end), T_1 is the maximum value of lead time (in the front end) and r is the discount rate. A simplified method of estimating the fuel costs prior to levelising the annual costs is detailed in [13].

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5.7 *Levelised Decontamination and Decommissioning (D&D) Costs*

The D&D funds accumulate over the operational life of the plant into the sink fund as expressed below:

$$DD = CDD \cdot SFF(r_{real}, L_{econ}) \tag{39}$$

whereby DD is the annual constant dollar payment to the D&D sinking fund, CDD is the decommissioning costs, $SFF(r_{real}, L_{econ})$ is the sinking fund factor at a rate of r for a time period in years of t, which is expressed as:

$$SFF(r,t) = \frac{r}{[(1+r)^t - 1]} \tag{40}$$

Thus, the D&D can be levelised and expressed as:

$$LDD = \frac{DD}{P_{elec\_annual}} \tag{41}$$

5.8 *Levelised Unit Electricity Cost (LUEC)*

The LUEC is calculated after deriving the aforementioned components of the economic model. This is expressed as:

$$LUEC = LCC + \sum \frac{[(OM+FCC+DD)(1+r)^{-t}]}{\left[P_{elec_{annual}}(1+r)^{-t}\right]} =$$

$$LCC + \frac{[(OM+FCC+DD)\sum(1+r)^{-t}]}{\left[P_{elec_{annual}}\sum(1+r)^{-t}\right]} =$$

$$LCC + \left[\frac{(OM+FCC+DD)}{P_{elec_{annual}}}\right] \tag{42}$$

6. Method of Modelling of Nuclear Power Plants - Risk Model

The risk assessment capabilities within the model focuses on four areas as described in [17]:

1. Risks associated with design impact studies / improvements.
2. Risks associated with 'lower than design intended' cycle performance.
3. Risks associated with plant operation.
4. Risks associated with financing the capital and D&D.

For this study, areas 2-4 are being considered. These are described in the proceeding sub-sections:

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6.1 Cycle performance

The technical analyses of factors affecting performance are detailed in [2]. The analysis concluded that component efficiencies and pressure losses consequentially affect plant power output. The technical model is used to calculate the conditions; the outputs are subsequently used to assess the effect on the LUEC.

6.2 Plant Operation

The risks associated with operating the plant take into account operating in Off-Design (OD) mode, whereby the plant inlet conditions are altered, or part power operation is demanded. The technical analyses are detailed in [9]–[11] for long term OD operation and part power load control and following methods. Plan conditions are altered by changes in inlet temperature or COT. The conditions are calculated in the technical model and the outputs are used to assess the effect on the LUEC.

6.3 Financial Risks

These financial risks are concerned with unfavourable discount rates, variation in capital and operational costs and increased D&D due to changes in discount rates. These are considered important because they aid sound financial judgement of the financial risks and their impact impact on the final LUEC. These are calculated using the economic model.

Where changes to plant performance, operation or the financing costs conditions affect the costs, these sensitivities are assessed and combined. The combined summation (average) of the worst-case specific LUEC for each risk in terms of sensitivities and adverse effect on the plant, is added to the 'non-contingency' LUEC of the plant to deduce the final LUEC.

7. Results and Discussion

7.1 Effect of Component Efficiencies (Cycle Performance Risk)

The results of the derived plant configurations with the highest efficiencies are listed in Table 2. Technically, The lower ranges of compressor and turbine efficiencies have a greater impact on both cycles. For the compressor, the lower component efficiency range reduces the plant cycle efficiency by 1.1% (SCR) and 0.9% (ICR) because more work is required by the compressors to raise the helium to the required pressure. However, the ICR is more sensitive to reduction in turbine efficiencies due to reduced power extraction from the hot gas pressure. This translates into a 1.4% drop in plant cycle

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efficiency for the ICR and is more than the SCR (1.2%) for the 0.85<η<0.89 component efficiency range. The recuperator has the greatest effect on cycle efficiency for the SCR (1.6% drop) and ICR (1.8% drop) at the 0.85<ε<0.89 recuperator effectiveness range. This is because of the reduced quality of the heat exchange of the turbine exhaust gas back into the cycle to raise the temperature of the helium going into the reactor.

Figure 3 illustrates the component efficiencies for the ICR and their individual effect on the plant cycle efficiency (η_{th}). The results for the ICR are comparable to the SCR. These results including the results for the SCR, are illustrated and discussed in detail in a previous study by the authors' in [2]. In terms of quantifying the risk, the analyses looked at a reduction of 5% in compressor efficiency, 10% in turbine efficiency and 11% in recuperator effectiveness for both cycles from their DP input values (Table 1). Based on the above reductions from the DP levels in Table 1, the average cost of all 3 components combined is $5.84/MWh for the SCR and $5.36/MWh for the ICR. The recuperator cost effect on the ICR is larger but the SCR has a bigger cost effect due to the turbine.

Table 2 – SCR and ICR Technical Design Point Output Results and Baseline Cost

Design Point Performance Output Results	SCR	ICR	Units
Reactor Core Inlet Temp (CIT) (T_3)	645	590	°C
Overall Pressure Ratio (OPR)	2.2	2.6	-
Compressor Work (CW)	263.7	299	MW
Turbine Work (TW)	585.3	705	MW
Reactor Heat Input	642.9	761	MW
Specific Work (SW) (NPP Capacity)	0.78	0.99	J/kgs K
Useful Work (UW)/ Power Output	321.6	405.8	MW
Plant Efficiency	50	53	%
Baseline 'non-contingency' Levelized Unit Electricity Cost (LUEC)	58.41	58.70	$/MWh

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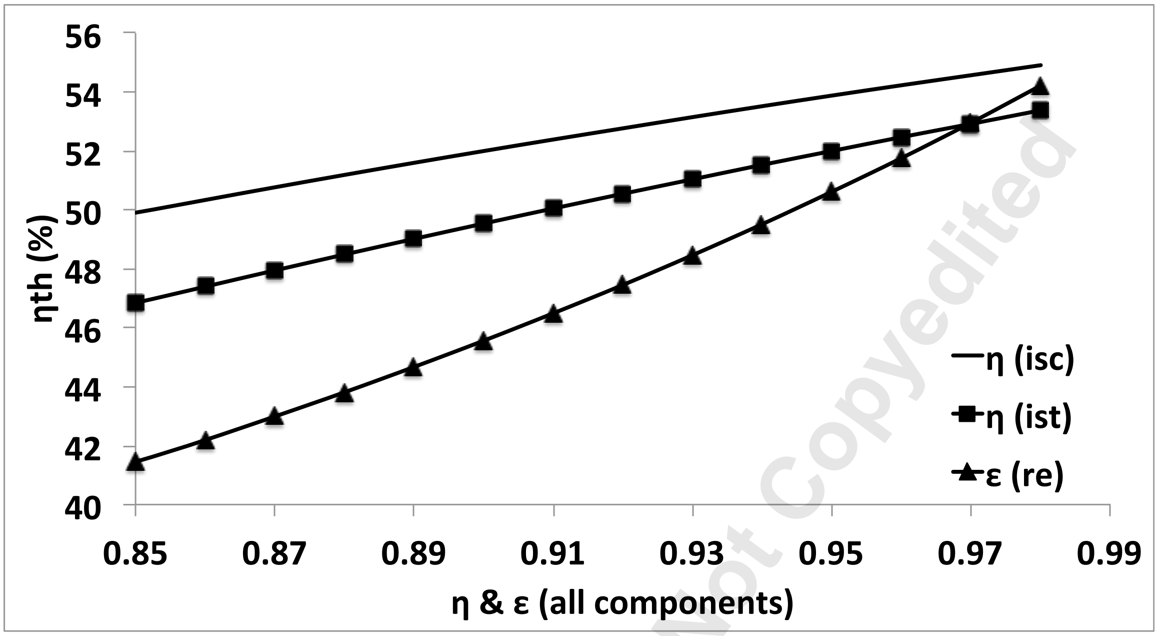

Figure 3 – Effect of Component Effciencies on Cycle Efficiency (ICR)

7.2 Effect of Cycle Pressure Losses (Cycle Performance Risk)

Figure 4 illustrates the effects of specific component pressure losses (between 0.5 and 5%) on the cycle efficiency of the ICR (η_{th}). It focuses on the pressure losses in the reactor, precooler, recuperator and intercooler. The analysis looks at individual component effects without changing the DP pressure losses (see table 1) of the other components of interest. The results trend is similar for the SCR although the SCR does not have an intercooler. The risk analyses looked at pressure losses between the 0.5 – 5% range for each component. Based on Figure 4, it can be observed that the effects of pressure losses on cycle efficiency have a negative correlation for every component being investigated. When the focus is on the cycles, the ICR is more sensitive to the recuperator High Pressure (HP) side, reactor and intercooler pressure losses. This is also the case for the SCR but without an intercooler. The effects of pressure losses on the cycle as described in figure 4 including the results for the SCR, are illustrated and discussed further in a previous study by the authors' in [2]. When analysing the risk of operating with pressure losses at the extreme values of 5% per component in comparison to the DP pressure losses (see Table 1), the average cumulative cost of all the component pressure losses combined is \$4.08/MWh for the SCR compared to \$3.05/MWh for the ICR. The reason for the higher cost to the SCR is because the recuperator HP results in a greater drop in power output, which

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affects the LUEC. This is irrespective of the greater cumulative effect of the pressure losses on the cycle efficiency of the ICR (because of the additional intercooler), whereby the drop in the ICR cycle efficiency is greater by 1% in comparison to the SCR.

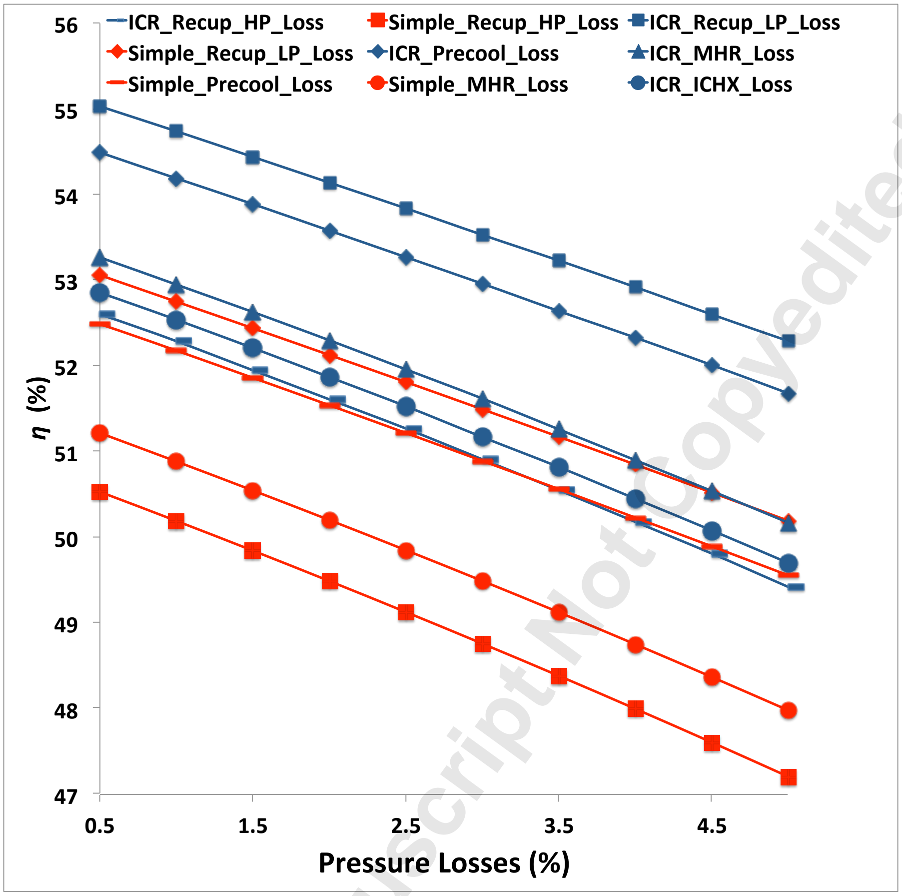

Figure 4 – Effect of Component Pressure Losses on Cycle Efficiency (ICR)

7.3 *Effect of Long and Short Term Off-Design Operations (Plant Operation Risks)*

As described, the circumstances associated with this risk include the effect of precooler outlet/compressor inlet temperature on meeting load demand, the variation of load demand to operate at part power for short term purposes and for long term, a reduction in power capacity due to long term seasonal temperature changes or to prioritise other sources such as renewables on the grid. One thing to note is the operational aspect is a risk that is managed after the plant has been built but it is important to consider it at an early stage. Figure 5 provides the times for short-term IPC operation due to changes in compressor inlet temperature (5°C changes). It demonstrates how quickly each cycle is able to modulate the power. The IPC is used to control the NPP to not exceed reactor thermal power for integrity purposes. Tables 3 and 4 show the effects of variation in compressor inlet temperature on the power output and quantifies the risk for the SCR and ICR respectively.

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Operating above the DP compressor inlet temperature means a greater compromise of the power output for the SCR in comparison to the ICR when maintaining reactor thermal power. However, when the average LUEC based on a compressor inlet temperature of 0°C to 50°C is analysed, there is a positive benefit for the LUEC, because at lower than DP compressor inlet temperatures, there is an increase in plant capacity. This benefit results in an average LUEC that is 35$ct less per MWh for both cycles. There are greater benefits for the LUEC if the NPP operates at even lower compressor inlet temperatures. The ICR at lower compressor inlet temperatures provides the bigger benefits for the LUEC. The potential gains from operating at lower compressor inlet temperatures are not considered in the final LUEC (post risk assessment). This is to ensure conservatism in the price. Tables 5 and 6 show the effect on the LUEC when the NPP is operated at part power using the IPC method. The power level is reduced by up to 50% of power output. An average LUEC increase of $18/MWh across the power range is observed, with the SCR having a negligibly larger increase. It is possible that the NPP will operate at a reduced power output for short periods using IPC and for long periods when the reactor power will be adjusted to meet prioritisation for renewables. As such, the final LUEC (post risk assessment) takes into account OD operation based on a plant availability, which is a reduction of 20% per year. Other effects of compressor inlet temperature are covered in [18].

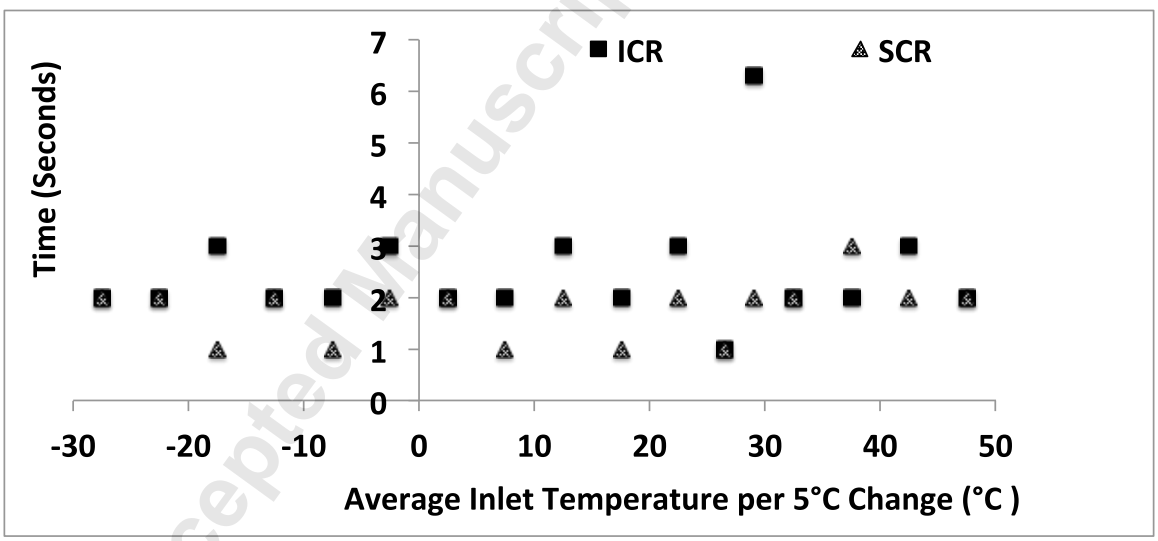

Figure 5 – Load-Following Performance Times (Seconds) based on Compressor Inlet Temperature to Maintain Reactor Thermal Power

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Table 3 – Quantification of Operating at Various Inlet Temperatures to Maintain Reactor Power (SCR)

Off-Design (Load-Following Inventory Control)		
Compressor Inlet (°C)	Capacity (MW)	Delta ($/MWh)
50	305.8	2.48
40	313.2	1.31
30	320.4	0.24
28 (DP)	322	0
20	328	-0.85
10	335.7	-1.63
0	343.3	-2.9
-10	350.9	-3.85
-20	358.6	-4.76
-30	365.9	-5.6
		-0.19cts/MWh (Average from 0°C to 50°C)

Table 4 – Quantification of Operating at Various Inlet Temperatures to Maintain Reactor Power (ICR)

Off-Design (Load Following Inventory Control)		
Compressor Inlet (°C)	Capacity (MW)	Delta ($/MWh)
50	394.5	1.38
40	400.4	0.66
30	406.4	-0.04
28 (DP)	406	0
20	413.6	-0.87
10	423.2	-1.9
0	432.9	-2.91
-10	442.4	-3.86
-20	452.4	-4.82
-30	461.5	-5.65
		-0.53cts/MWh (Average from 0°C to 50°C)

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Table 5 – Quantification of Operating at Reduced Power Settings (SCR)

DP Part Load Performance (Inventory Control)		
Power %	**Capacity (MW)**	**Delta ($/MWh)**
100	322	0
90	289.8	4.92
80	257.6	11.06
70	225.4	18.96
60	193.2	29.48
50	161	44.22
		$18.11/MWh (Average of operating at the analysed power settings)

Table 6 – Quantification of Operating at Reduced Power Settings (ICR)

DP Part Load Performance (Inventory Control)		
Power %	**Capacity (MW)**	**Delta ($/MWh)**
100	406	0
90	365.4	4.87
80	324.8	10.95
70	284.2	18.75
60	243.6	29.16
50	203	43.73
		$17.91/ MWh (Average of operating at the analysed power settings)

7.4 Effects of Financial Risks on the Capital

The risks associated with the capital, operational finance and end of life of the NPP is based on understanding the sensitivities of the individual costs. Table 7 provides a list of the cost areas that are used to assess the cycles. Figure 6 shows a graphical representation of how each cost affects the LUEC. The LUEC in this illustration applies to the SCR.

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Table 7 – Capital and Operating Cost Sensitivities and Tolerances

Number on Bar Chart	Group Sensitivities	Tolerance
1	Plant Capacity	±2%
2	Plant Life	±2%
3	Construction Period	4years; 10years
4	Discount Rate	3%; 10%
5	Decontamination & Decommissioning Costs	±2%
6	Non Fuel Ann Recurring Costs	±2%
7	Fuel Cycle	±2%
8	Preconstruction Costs	±2%
9	Building Structure	±2%
10	Reactor	±2%
11	Turbomachinery	±2%
12	Electrical Equipment	±2%
13	Water Intake & Heat Rej.	±2%
14	Miscellaneous	±2%
15	Support Services	±2%
16	Operating Costs	±2%
17	Schedule Contingency	±10%
18	Reactor Performance Contingency	±10%

Figure 6 applies to the SCR but the results are also applicable to the ICR. The LUEC in the analyses shown in Figure 6 is for a plant capacity of 92%, with contingency on capital of 25%, contingency of 20% on availability to include OD operations and a reactor performance contingency of 20%. This brings the LUEC to $61.84/MWh (SCR) and $62.13/MWh (ICR).

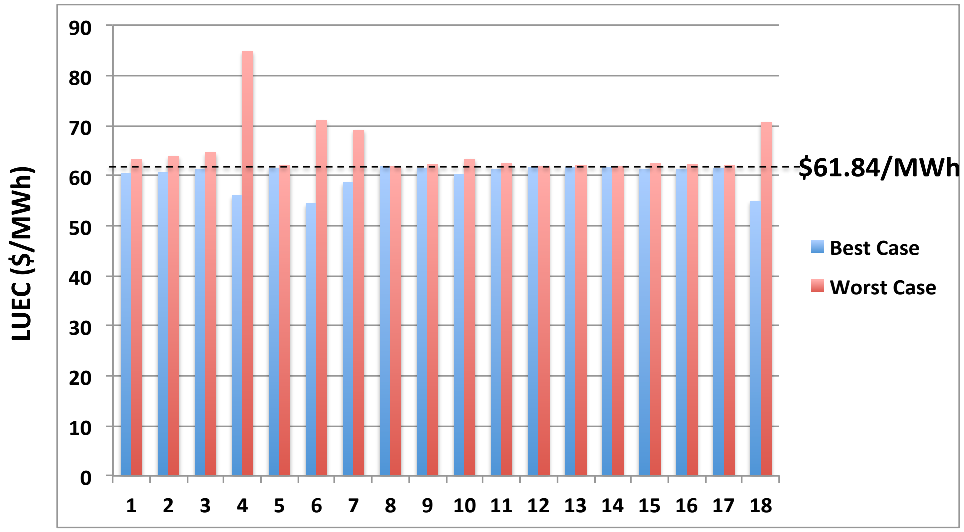

Figure 6 – Sensitivities of Capital and Operational Costs (SCR). See Table 7 for Bar Chart Legend.

The results indicate that the discount rate, operational non-fuel recurring costs, fuel cycle and reactor performance have the biggest impact on the NPP LUEC. The discount rate assumes the minimum and maximum values that can be applied to an NPP project, whilst the reactor performance has a ±10% tolerance due to the combined OD operations and uncertainty in reactor performance for the GFR and VHTR concept designs. However, the operational non-fuel annual costs and the fuel cycle costs are the most sensitive due to the fact that these costs are annually applied over the operational life of the NPP.

With regard to the discount rate and the Decontamination and Decommissioning (D&D) costs, it is worth pointing out that a ±2% sensitivity on the D&D cost has a negligible effect on the LUEC. For the SCR, the cost variation of 2% is ±$0.26ct/MWh, whereby a reduced D&D cost means a reduced overall LUEC. However, when the discount rate is altered by ±2% on the D&D alone, the LUEC is ±$1.66/MWh, whereby a reduced discount rate means an increased LUEC. This represents an increase of 640% on the LUEC due to altering the discount rate on the D&D and highlights a key problem in civil NPP projects. The significantly high start up and end costs are unlike other generating sources. The sensitivity of the D&D activity is as a result of the discount rate, which is used to determine the sink fund factor. Thus a lower discount rate that improves the overall LUEC will increase the amount that has to be paid at the end of life to complete the D&D activity.

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7.5 *Final LUEC for Year 2020 with Quantified Risk Contingencies*

The final LUEC for year 2020 is determined by adding the average worst-case increases in LUEC. It relates to the capital and operational finances and the cycle performance and includes the worst-case contingency for reactor performance, which considers a reduced availability of the NPP. It does not include the benefits of operating the NPP at lower temperatures whilst performing load-following operations. This worst-case combined LUEC (based on the worst case cost of every risk assessed) is added to the 'non contingency' baseline LUEC (which includes some availability contingency) to arrive at the final LUEC for each Gen IV helium cycle for the year 2020. For the SCR, the LUEC without the calculated risks is increased by 20% from $58.41/MWh to $71.62/MWh. For the ICR, the inclusion of the calculated risks raises the LUEC by 17% from $58.70/MWh to $70.45/MWh. The final LUECs indicated that the initial estimates with some contingency (capital and reactor performance), which resulted in $61.84/MWh (SCR) and $62.13/MWh (ICR) were not sufficient because the other performance and plant operational aspects were not analysed and considered. The average total of the capital and operational financial contingencies, which include combined reactor performance, represent 5 to 6% of the total final LUEC for the cycles. Component effectiveness, efficiencies and pressure losses amount to 14% (SCR) and 12% (ICR) of the final LUEC. The initial costs of $58.41/MWh (SCR) and $58.70/MWh (ICR) included 16% plant availability contingencies. These include operating the NPP in OD part power settings. The methodology used to derive the final LUEC is judged to be appropriate because it is an average weighted worst-case value arrived at by summing availability (plant operation), performance, capital and operational finance risks. It is worth noting that the LUECs represent Nth of a Kind (NOAK) investments, meaning all cost and uncertainties associated with the development of the cycles have not been included. A key area that needs to be investigated is whether the most efficient plants are the most economical in terms of price. This is important in order to ensure that the configurations are driven by economics to make the plants more competitive with other generating sources.

8. Conclusion

In summary, the objective of this paper is to conduct technical and economic risk analyses associated with the plant design, performance operation and capital finance and to assess the effect on the 'non-contingency' baseline Levelised Unit Electricity Cost (LUEC). The analyses is performed using a tool specifically design for this study to analyse the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) in a closed Brayton direct configuration using helium as the working fluid. The technical, economic and risk models and results provide good bases to support the decision-making process

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on choice of cycles during the preliminary design phases of the Gas Cooled Fast Reactors (GFR) and Very High Temperature Reactors (VHTR) for Generation IV NPPs. The main conclusions are:

- Generation IV (Gen IV) reactor performance and economics are key imperatives for the design and competitiveness of Nuclear Power Plants (NPP) in comparison to the incumbent design and other sources of power generation.
- A technical, economic and risk model has been created for this study to quantify the risks associated configurations that are based on the most efficient plants. The model provides a method of combining the technical, economic and risk analyses and evaluations to aid the decision-making process for operators. The results of the technical model prioritises the efficiency over the plant capacity for the economic and risk analyses. For the input values considered, efficiencies of 50% and 53% were derived for the SCR and ICR respectively. The calculated 'non-contingency' LUEC are $58.41/MWh (SCR) and $58.70/MWh (ICR).
- With regard to the risk of operating with low component efficiencies, the average cost of all 3 components (compressor, turbine and recuperator) are $5.84/MWh for the SCR and $5.36/MWh for the ICR. The recuperator cost effect on the ICR is larger but the SCR has a bigger cost effect due to the turbine.
- When focusing on the risk of operating with very high pressure losses, the average cumulative cost of all the component pressure losses is $4.08/MWh for the SCR compared to $3.05/MWh for the ICR. The reason for the higher cost to the SCR is because the recuperator High Pressure (HP) side results in a greater drop in power output, which affects the LUEC. This is irrespective of the greater cumulative effect on the cycle efficiency of the ICR whereby a drop in the ICR cycle efficiency is greater by 1% in comparison to the SCR.
- There is no negative effect on the LUEC when operating the plants across an inlet temperature range of 0°C to 50°C. At extremely lower temperatures, the effect on the price is positive due to the extra power output generated. When reducing the power output due to grid prioritisation for renewables sources, the effect on the LUEC can add as much as $18/MWh (average) to the final cost of the plant, with this cost increasing if operated regularly at up to 50% reduced power. However, a 20% reduced availability is considered in the final LUEC.
- For the financial risks, the results indicate that the discount rate, operational non-fuel recurring costs, fuel cycle and reactor performance have the biggest impact on the NPP LUEC. For the the Decontamination and Decommissioning (D&D) costs, the sensitivity is as a result of the discount rate, which is used to determine the sink fund factor. Thus a

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lower discount rate that improves the overall LUEC will have increased the amount that has to be paid at the plant's end of life in order to complete the D&D activity.

- For the SCR, the LUEC without the calculated risks is increased by 20% from $58.41/MWh to $71.62/MWh. For the ICR, the inclusion of the calculated risks raises the LUEC by 17% from $58.70/MWh to $70.45/MWh. The final LUECs indicated that the estimates with some contingency (capital and reactor performance), which resulted in initial calculated costs of $61.84/MWh (SCR) and $62.13/MWh (ICR) were not sufficient in determining the true cost of the contingencies. The final LUECs represent the costs of the various cycles for year 2020.
- A key area that needs to be investigated is whether the most efficient plants are the most economical in terms of price. This is important in order to ensure that the configurations are driven by economics to make the plants more competitive with other generating sources.
- Validation is recommended for the tools such as the one developed for this study. This will enable optimisation to improve the applicability and accuracy and will encourage its use thereby reducing costs associated with extensive test activities and inaccurate analyses and cost estimations.

9. Acknowledgements

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10. Conflicts of Interest

The authors declare no conflict of interest.

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